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Medical Science

To Cite:
Al-Haji H, Al-Qahtani J, Al-Aliani AN, Abahoussin OK, Alshehri T, Al-Mesned M, Alanazi TA, Al-Shammari Y, Al-Aqeily A. Long term effects of mechanical ventilation on lung function in critical care patients: Systematic review. *Medical Science* 2024; 28: e77ms3392
doi: https://doi.org/10.54905/disssi.v28i149.e77ms3392

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Peer-Review History
Received: 29 April 2024
Reviewed & Revised: 03/May/2024 to 09/July/2024
Accepted: 13 July 2024
Published: 21 July 2024

Peer-review Method
External peer-review was done through double-blind method.

Medical Science
pISSN 2321–7359; eISSN 2321–7367

DISCOVERY SCIENTIFIC SOCIETY

Long term effects of mechanical ventilation on lung function in critical care patients: Systematic review

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ABSTRACT

Background: Weaning the patient off the ventilator becomes difficult when the diaphragm contraction ability deteriorates, which often occurs after a prolonged period of mechanical ventilation. In this study, our goal was to analyze previous research showing that patients in intensive care units have diaphragmatic dysfunction and respiratory muscle atrophy brought on by mechanical ventilation. *Method:* The present systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. Utilizing the medical phrases diaphragm, respiratory muscle, mechanical ventilation, and lung function. To find relevant publications published between 2008 and 2024, we searched PubMed/Medline and SCOPUS extensively for relevant literature. The study types that we searched were observational studies, cohort studies, clinical trials, and randomized controlled trials. *Result:* Ten articles examining the impact of mechanical ventilation on lung function and respiratory muscle were included in the analysis; three research employed histology, and seven studies used ultrasound as an assessment method. Acute respiratory failure, extended MV periods, and ICU hospitalizations are associated with progressive diaphragm atrophy during MV. In a statistically meaningful way, neurologically adjusted ventilation assists lowers the incidence of diaphragm malfunction. *Conclusion:* Diaphragmatic rest and mechanical ventilation result in the atrophy of diaphragm myofibers considerably. An increase in diaphragmatic proteolysis during inactivity was observed during prolonged MV. Diaphragm atrophy brought on by MV significantly affects the outcomes.

Keywords: Mechanical ventilation, Lung Function, Diaphragm atrophy, Diaphragm contractility.

1. INTRODUCTION

In acute or emergent situations, mechanical ventilation (MV) is an essential intervention to save lives, especially for patients with impaired breathing, hypoxemic respiratory failure, or damaged airways. The compliance and resistance of the airway system are crucial to this process, which entails providing positive pressure breaths (Hickey et al., 2024). The diaphragm frequently has a poor contraction ability when breathing spontaneously again after a lengthy period of MV, which makes it challenging to wean the patient off the ventilator. Ventilator-induced diaphragm dysfunction (VIDD) is brought about by diaphragm fiber atrophy, inspiratory muscle weakening, and contractile failure during the MV process (Petrof et al., 2010; Demoule et al., 2016). This is important because difficulties in weaning patients off of the ventilator result in prolonged use of a ventilator, which raises health care expenses and significantly raises morbidity and death rates in patients. According to Powers et al., (2013) study, just 18 to 24 hours of MV are needed to cause VIDD.

Recent research showed that diaphragmatic atrophy with more than half reduction in fibre cross sectional area) of both type I and type II muscle fibres in the costal diaphragm occurs after 18 to 69 hours of full support mechanical ventilation (Levine et al., 2008). This initial result was recently validated in another investigation showing that diaphragmatic fiber atrophy happens in persons subjected to full support mechanical ventilation for at least twenty-four hours, and that the degree of diaphragmatic atrophy is strongly connected with the length of mechanical ventilation (Jaber et al., 2011). Furthermore, a recent observational study that evaluated diaphragmatic thickness using serial ultrasound scans found that diaphragm weakening happens 48 hours after partial support MV begins (Grosu et al., 2012). All together, these human studies show that diaphragm muscle fibres rapidly atrophy as a result of prolonged MV. In this research, we aimed to review studies that identified diaphragmatic dysfunction and respiratory muscle atrophy induced by MV in ICU patients.

2. METHOD

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) standards were followed in the conduct of this systematic review. Making use of the medical terms "lung function", "mechanichal ventilation", "respiratory muscle", and "diaphragm". In order to locate pertinent papers between 2008 and 2024, we conducted a thorough literature search in PubMed/Medline and SCOPUS. Randomized controlled trials, clinical trials, observational studies, and cohort studies were the study types searched. The following free search terms were used: “Mechanical ventilation”, “invasive mechanical ventilation”, "prolonged mechanical ventilation", “intensive care unit”, “ICU”, “lung function”, “respiratory muscle function”, “diaphragm”, “diaphragmatic”, “atrophy”, “diaphragm function” “diaphragm atrophy”, “diaphragm thickness”, and “diaphragm contractile dysfunction”.

The articles chosen met the following inclusion criteria: Patients received MV in the ICU, and outcomes included evaluation of diaphragm contractility function and diaphragm thickness. The authors independently searched for these criteria. We examined the abstracts and titles to find studies that could be appropriate and fit the inclusion criteria. Two writers independently evaluated every article to ascertain whether the research satisfied the inclusion criteria after the references were judged pertinent. We excluded reviews, animal studies, comments, case reports, and duplicates. Both original readers also hand-sorted the reference lists of relevant papers in an effort to find additional studies that satisfied the qualifying requirements.

A third reviewer has overseen the strategy for search and inclusion. A total of 98 articles were initially collected from databases. After the removal of duplication and abstract and title screening, 35 full-text articles remained. Of these, 25 were excluded for reasons (Figure 1), and the remaining 10 studies were included in the review. The reviewers independently retrieved data from the studies. They gathered the research's designs, sample sizes, evaluation techniques (ultrasound or histology), objectives, primary findings, and conclusions. When a consensus could not be reached, a third reviewer was consulted to resolve conflicts.

3. RESULTS

We included 10 articles investigating the effect of prolonged MV in respiratory muscle and lung function; seven studies used ultrasound as assessment tool Hadda et al., (2022), Pearson et al., (2022), Zambon et al., (2016), Schepens et al., (2015), Grosu et al., (2012), Goligher et al., (2015), Goligher et al., (2018), and 2 studies used histology (Hooijman et al., 2015; Jaber et al., 2011) (Table 1). Progressive diaphragm atrophy is linked to prolonged MV times and ICU stays (Jaber et al., 2011; Goligher et al., 2018; Goligher et al.,

2015; Hooijman et al., 2015). Prolonged breathing was indicated by early rapid increases in diaphragm thickness, raising the possibility of clinically substantial diaphragm injury from inadequate respiratory muscle rest during ventilation (Goligher et al., 2018). Significant atrophy of diaphragm myofibers was observed in study in combination with total diaphragmatic rest and mechanical breathing, in addition to an increase in diaphragmatic UPP during inactivity.

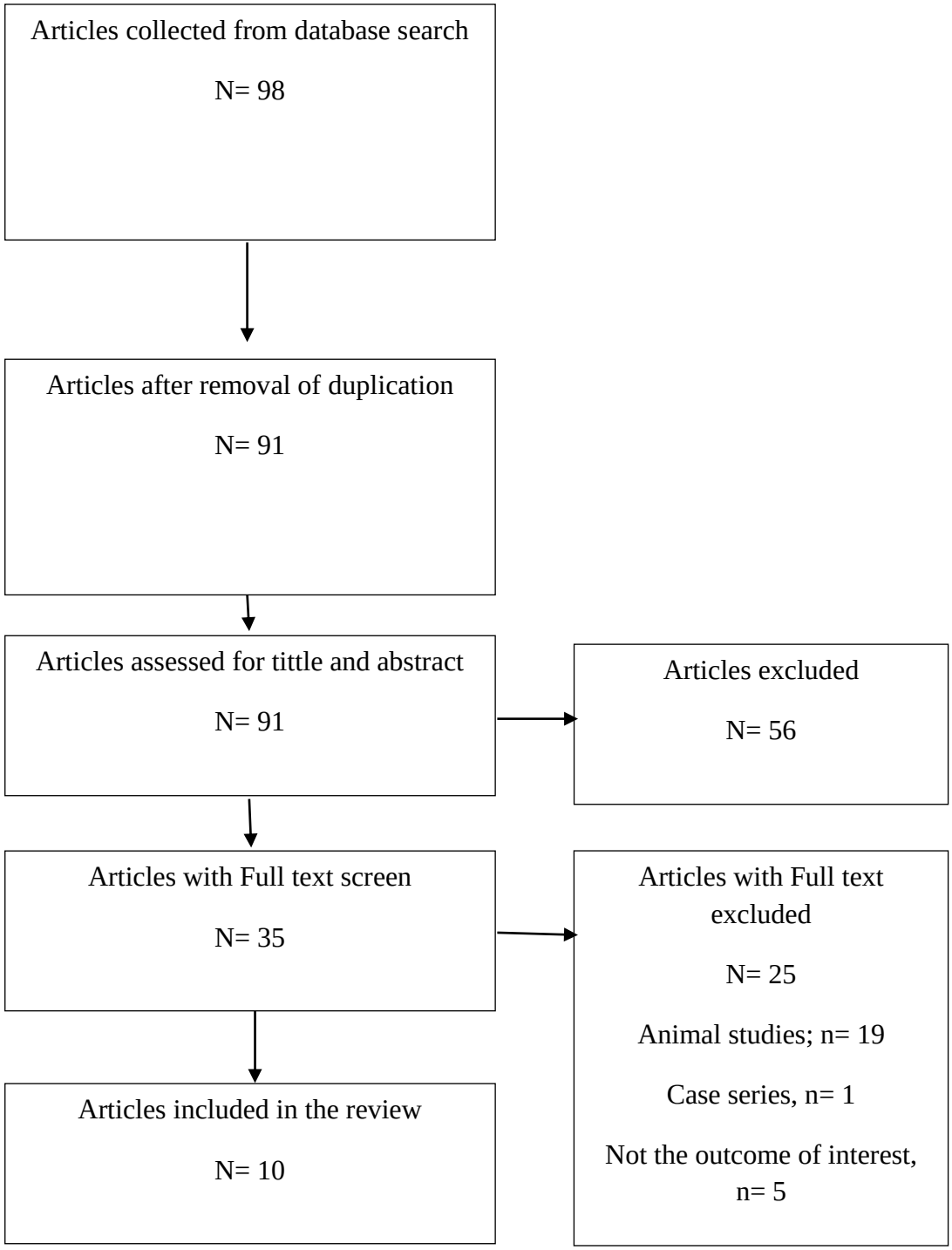

Figure 1 PRISMA consort chart of studies selection

Titrating ventilatory assistance to maintain inspiratory effort normal levels may minimize changes in diaphragm thickness caused by MV (Goligher et al., 2015). Two of the included studies Hooijman et al., (2015), Jaber et al., (2011) observed that the ubiquitin-proteasome pathway (UPP) was markedly elevated in the diaphragm of ICU patients (Table 2). According to Jaber et al., (2011), airway occlusion pressure decreased gradually during MV, reaching a mean of 32% after 6 days. Longer periods of MV were associated with significantly greater ultrastructural fibre damage and reduced cross-sectional area of muscle fibres (Schepens et al., 2015; Jaber et al., 2011). The diaphragm muscles diminish 48 hours after beginning MV, according to a study by Grosu et al., (2012). It is unclear, though, if this impacted lung function.

Zambon et al., (2016) reported that the average daily atrophy rate was -7.5% during controlled MV, -5.3% in high-pressure support ventilation, -1.5% in low-pressure support ventilation, and +2.3% during spontaneous breathing or continuous positive airway pressure. Changes in MV mode or sedative discontinuation had rapid effects on diaphragm thickness measurements in adult ICU patients on MV (Pearson et al., 2022). After stopping sedatives in Pearson et al., (2022) study, the end-expiratory diaphragm thickness increased by a median of 0.08 mm, or 6.5%. There was no noticeable difference between the measurements for volume assist control and pressure support. Switching from traditional MV to Neurally Adjusted Ventilation Assist reduces the incidence of diaphragm dysfunction in a statistically significant manner (Hadda et al., 2022).

Table 1 Included studies characteristics

Citation	Sample size	Study aim	Method	Assessment method
Goligher et al., 2018	191	To test if diaphragm atrophy caused by MV results in longer ventilation.	In adults need MV, diaphragm thickness was evaluated daily using ultrasonography, and inspiratory effort was estimated using thickening fraction. The major outcome was the amount of time required to be free of ventilation. Complications included re-intubation, tracheostomy, extended ventilation, and death. The associations were adjusted for infection, age, severity of disease, neuromuscular blockade, comorbidities and sedation.	Ultrasound
Levine et al., 2008	Case group 14 Control group 8	The authors hypothesized that the combination of full diaphragm inactivity and MV causes atrophy of myofibers in patients.	The authors collected costal diaphragms biopsy specimens from 14 brain-dead organ donors (case subjects) and contrasted these with intraoperative biopsy samples taken from the diaphragms of eight individuals (control participants) who were having surgery for localised lung cancer or benign lesions. In contrast to control participants, who only needed MV for two to three hours, case patients were diaphragmatically inert and needed it for eighteen to sixty-nine hours.	Histology
Goligher et al., 2015	117	To describe how diaphragm thickness changes during MV, how it affects diaphragm function, and how inspiratory effort influences this phenomena.	In three academic ICU, 107 patients were admitted shortly after starting ventilation, together with 10 non-ventilated ICU patients. Ultrasound was used daily to quantify contractile activity and diaphragm thickness by the inspiratory thickening fraction.	Ultrasound
Hooijman et al., 2015	22	To know if diaphragm muscle fibres in ICU patients on MV exhibit	Authors collected diaphragm muscle samples from 22 ICU patients on MV before surgery and compared them to biopsies taken from patients undergoing thoracic surgery	Histology

		atrophy and contractile weakening, and that the UPP is active in the diaphragm.	for removal of a suspected lung cancer (control subjects).	
Jaber et al., 2011	25	To predict the time course of diaphragmatic weakness development during MV	In both the short-term and long-term MV groups, the airway occlusion pressure produced by the diaphragm during phrenic nerve stimulation was measured. Diaphragmatic biopsies obtained from brain-dead organ donors and following thoracic surgery were analyzed for expression of proteins linked to proteolysis, ultra structural damage, and atrophy.	Histology
Grosu et al., 2012	7	To measure the diaphragm atrophy during MV.	Thickness of diaphragm muscle was monitored daily using sonography from the start of MV until the patient died, extubated, or had a tracheostomy.	Ultrasound
Schepens et al., 2015	54	To investigate the clinical progression and risk factors for diaphragmatic dysfunction in an adult ICU, diaphragm thickness was measured using ultrasound.	Observational cohort study with 54 mechanically ventilated patients. Every day, the right hemidiaphragm was measured at its apposition zone on the midaxillary line.	Ultrasound
Zambon et al., 2016	40	Using ultrasound, assess diaphragm atrophy in ICU patients on MV.	In this observational prospective study, daily atrophy rate was estimated as the percentage decrease from the preceding measurement. The daily atrophy rate was divided into four categories: pressure support ventilation 5 to 12 cm H2O, regulated MV, continuous positive airway pressure or spontaneous breathing, and more than 12 cm H2O pressure support ventilation.	Ultrasound
Pearson et al., 2022	85	To see if changes in MV mode or sedative interruption have an immediate effect on diaphragm thickness measures in adult ICU patients on MV.	Adult patients who had undergone MV for fewer less than 48 hours were included. Ultrasound was used to quantify diaphragm thickness at the end of expiration and peak inspiration while patients were treated in a randomized crossover way with pressure-support modes and volume assist-control. Additional measurements were collected in sedative-treated patients after the sedatives were stopped. Measurements were evaluated between modes and assist-control after and before sedative discontinuation.	Ultrasound
Hadda et al., 2022	46	Diaphragm dysfunction was assess between traditional modalities of MV and Neurally Adjusted Ventilation Assist (NAVA).	Patients who were placed on MV for ARF were randomly assigned to either continue with traditional MV or switch to NAVA. The incidence of diaphragm dysfunction was studied between two groups.	Ultrasound

Table 2 Conclusion and findings of studies included

Citation	Result	Conclusion
Goligher et al., 2018	The study's main finding is that progressive diaphragm atrophy during MV is associated with longer MV and ICU hospitalization, as well as an increased risk of ARF consequences. Diaphragm thickness rapid increases in extended breathing, enhancing the likelihood of diaphragm injury due to respiratory muscle insufficient unloading during ventilation.	Diaphragm atrophy resulting from MV has a significant impact on outcome.
Levine et al., 2008	The diaphragm biopsy specimens from the case individuals had smaller cross-sectional areas of fast-twitch and slow-twitch fibres, by 57% and 53%, respectively, than the specimens from the control group.	Human diaphragm myofibers significantly atrophy when MV and complete diaphragmatic rest are combined. An increase in diaphragmatic proteolysis during inactivity is consistent with our findings.
Goligher et al., 2015	During the first week of MV, diaphragm thickness reduced in 44% of patients by more than 10%, remained constant in 44%, and increased by 10% in 13 patients. Thickness did not change with time after extubation or in individuals not on MV. Diaphragm atrophy rapidly when contractile activity was low, but increased when contractile activity was high. Contractile activity decreased with increased ventilator driving pressure and regulated ventilator modes.	Diaphragm thickness variations are typical during MV and may indicate diaphragmatic weakening. Titrating ventilatory assistance to maintain normal levels of lung function may minimize changes in diaphragm thikness caused by MV.
Hooijman et al., 2015	Both fast- and slow-twitch diaphragm muscle fibres in severely ill individuals showed a 25% lower cross-sectional area and a contractile force reduction of 50% or more. Markers of the UPP were markedly elevated in the diaphragm of ICU patients.	Diaphragm muscle fibres in critically ill individuals exhibit contractile weakening and atrophy. UPP is activated in the diaphragm.
Jaber et al., 2011	Airway occlusion pressure reduced gradually throughout MV, reaching a mean of 32% after 6 days. Longer duration of MV were linked with considerably increased ultrastructural fibre injury, lower muscle fibres thikness, and an increase in activation of UPP.	Diaphragmatic weakening, damage, and atrophy occur rapidly in ICU patients on MV, and are significantly associated to the duration of MV.
Grosu et al., 2012	The rate of diaphragm thickness decrease for all patients over time was 6% per day of MV, which was substantially different from zero. Similarly, each patient's diaphragm thickness reduced over time.	Results reveal that diaphragm muscle weakening begins within 48 hours of MV commencement. However, it is unclear whether diaphragmatic thinning is associated with change in lung function.
Schepens et al., 2015	The mean baseline thickness was 1.9 mm, and the mean nadir was 1.3 mm, representing a 32% change in thickness. The duration of MV was linked with the degree of atrophy, while other established risk factors for muscular atrophy in an ICU were not. The most significant decrease in thickness happened within the first 72 hours of MV.	Diaphragm atrophy develops quickly in patients with MV and may be accurately evaluated using ultrasound. The duration of MV, rather than other variables, is connected with the degree of atrophy.
Zambon et al., 2016	The average daily atrophy rate was -7.5% during regulated	In ICU patients on MV, there is a direct

	MV, -1.5% during low pressure support ventilation, +2.3% during spontaneous breathing and -5.3% during high pressure support ventilation. In multivariate analysis, only ventilation support predicted diaphragm atrophy.	correlation between ventilator support and diaphragmatic atrophy rate.
Pearson et al., 2022	After discontinuing sedatives, end-expiratory diaphragm thickness increased by a median of 0.08 mm, or 6.5%. There was no discernible difference between measurements taken for volume assist-control and pressure support.	After discontinuing sedatives, the end-expiratory diaphragm thickness increased by 6.5%.
Hadda et al., 2022	The average diaphragm thickness fractions in the conventional MV and NAVA groups were 37% and 39%, respectively. Diaphragm dysfunction was reported in 22.7% and 34% of patients in the NAVA and conventional MV, respectively. There were no statistically significant differences between the groups. The NAVA group had better diaphragm excursion than the standard MV group. Thickness fractions and diaphragm thickness and were similar across the two groups.	Switching from conventional MV to NAVA results in a statistically insignificant reduction in the occurrence of diaphragm atrphy. Adequately powered investigations are required to determine the precise involvement of NAVA in diaphragm functions.

4. DISCUSSION

The combined studies indicate that longer MV durations are associated with increasing diaphragm atrophy. Early, fast increases in diaphragm thickness suggested prolonged breathing and increased the risk of clinically significant diaphragm injury due to insufficient respiratory muscle rest during ventilation. Modulating ventilatory support to sustain regular inspiratory effort levels could reduce variations in diaphragm thickness brought on by mechanical ventilation. ICU patients' diaphragms showed noticeably higher UPP in two of the included studies. According to Zambon et al., (2016), the average daily atrophy rate was 2.3% in spontaneous breathing or continuous positive airway pressure, -1.5% in low-pressure support ventilation, -5.3% in regulated mechanical ventilation, and -7.5% in controlled mechanical ventilation.

Diaphragm thickness measurements in adult ICU patients on MV were rapidly affected by changes in MV mode or cessation of sedatives, there was a median rise in end-expiratory diaphragm thickness of 6.5%, following the cessation of sedatives (Pearson et al., 2022). It is well known that muscle inactivity causes oxidative stress and raises the concentration of calcium in the cytosol. These disruptions are known to produce an increase in the activity of proteases, which in turn causes an increase in the dissociation of the myofibrillar lattice, a crucial first step in proteolysis (Du et al., 2004). An increased rate of protein release from the myofibrillar lattice is suggested by the increases in active caspase-3 and the decrease in diaphragmatic glutathione content, which is consistent with oxidative stress (Falk et al., 2006; Du et al., 2004; Lawler and Powers, 1998).

According to Goligher et al., (2018) study, targeting levels of inspiratory effort during ventilation equivalent to those of healthy patients breathing at rest may help potentially alleviate the prolonged ventilator dependence induced by detrimental diaphragmatic alterations occurring from ventilation. Diaphragmatic thickness tended to rise at greater inspiratory effort levels and decrease at lower inspiratory effort levels, according to the same study, indicating that an intermediate level would be ideal. Prior research has demonstrated that while excessive inspiratory efforts might worsen ventilator-induced lung injury Hudson et al., (2012) and damage the diaphragm Criswell et al., (1997), diaphragm inactivity promotes diaphragm atrophy. A brief cessation of sedatives significantly increased the measured diaphragm thickness in the Pearson et al., (2022) investigation, but the mechanical ventilation mode had no effect on the recorded diaphragm thickness.

These results are consistent with research by Rocco and colleagues (Rocco et al., 2017). They observed that propofol caused a temporary and reversible reduction in measured diaphragm thickness in patients having elective procedures while sedated during spontaneous breathing. The inability to remove the patient from the ventilator is one of the main issues related to prolonged MV. The rate of problematic weaning varies throughout ICUs but can reach approximately 30% of patients who have been subjected to

prolonged MV (Esteban et al., 1995; McConville and Kress, 2012). Patients who are unable to wean from the ventilator spend longer times in the hospital and have higher rates of morbidity and mortality (Esteban et al., 1994).

The weaning process can take up to 40% of the overall time spent on a ventilator in patients who are having trouble weaning and can take up to 60% of the total time (Esteban et al., 1994). Weaning failure can have a variety of root causes. Weaning issues may be largely caused by reduced respiratory muscle strength and endurance, despite disagreement (Eskandar and Apostolakos, 2007; Gayan and Decramer, 2002; Vassilakopoulos et al., 1996). However, because these trials are difficult to do in humans, there is a lack of concrete data showing cause and effect that diaphragm dysfunction is the primary cause of weaning issues.

5. CONCLUSION

Diaphragm myofibers significantly atrophy with diaphragmatic rest and MV. Prolonged MV was found to cause an increase in diaphragmatic proteolysis during inactivity. MV-induced diaphragm atrophy may result in weaning failure.

Funding

This study has not received any external funding.

Conflict of interest

The authors declare that there is no conflict of interests.

Ethical approval

Not applicable.

Data and materials availability

All data sets collected during this study are available upon reasonable request from the corresponding author.

REFERENCES

1. Criswell DS, Powers SK, Herb RA, Dodd SL. Mechanism of specific force deficit in the senescent rat diaphragm. Respir Physiol 1997; 107(2):149-55. doi: 10.1016/s0034-5687(96)02509-1
2. Demoule A, Molinari N, Jung B, Prodanovic H, Chanques G, Matecki S, Mayaux J, Similowski T, Jaber S. Patterns of diaphragm function in critically ill patients receiving prolonged mechanical ventilation: a prospective longitudinal study. Ann Intensive Care 2016; 6(1):75. doi: 10.1186/s13613-016-0179-8
3. Du J, Wang X, Miereles C, Bailey JL, Debigare R, Zheng B, Price SR, Mitch WE. Activation of caspase-3 is an initial step triggering accelerated muscle proteolysis in catabolic conditions. J Clin Invest 2004; 113(1):115-23. doi: 10.1172/JCI18330
4. Eskandar N, Apostolakos MJ. Weaning from mechanical ventilation. Crit Care Clin 2007; 23(2):263-74, x. doi: 10.1016/j.ccc.2006.12.002
5. Esteban A, Alía I, Ibañez J, Benito S, Tobin MJ. Modes of mechanical ventilation and weaning. A national survey of Spanish hospitals. The Spanish Lung Failure Collaborative Group. Chest 1994; 106(4):1188-93. doi: 10.1378/chest.106.4.1188
6. Esteban A, Frutos F, Tobin MJ, Alía I, Solsona JF, Valverdú I, Fernández R, De-la-Cal MA, Benito S, Tomás R, et al. A comparison of four methods of weaning patients from mechanical ventilation. Spanish Lung Failure Collaborative Group. N Engl J Med 1995; 332(6):345-50. doi: 10.1056/NEJM199502093320601
7. Falk DJ, Deruisseau KC, Van-Gammeren DL, Deering MA, Kavazis AN, Powers SK. Mechanical ventilation promotes redox status alterations in the diaphragm. J Appl Physiol (1985) 2006; 101(4):1017-24. doi: 10.1152/japplphysiol.00104.2006
8. Gayan-Ramirez G, Decramer M. Effects of mechanical ventilation on diaphragm function and biology. Eur Respir J 2002; 20(6):1579-86. doi: 10.1183/09031936.02.00063102
9. Goligher EC, Dres M, Fan E, Rubenfeld GD, Scales DC, Herridge MS, Vorona S, Sklar MC, Rittayamai N, Lanys A, Murray A, Brace D, Urrea C, Reid WD, Tomlinson G, Slutsky AS, Kavanagh BP, Brochard LJ, Ferguson ND. Mechanical Ventilation-induced Diaphragm Atrophy Strongly Impacts

Clinical Outcomes. Am J Respir Crit Care Med 2018; 197(2):204-213. doi: 10.1164/rccm.201703-0536OC

10. Goligher EC, Fan E, Herridge MS, Murray A, Vorona S, Brace D, Rittayamai N, Lanys A, Tomlinson G, Singh JM, Bolz SS, Rubenfeld GD, Kavanagh BP, Brochard LJ, Ferguson ND. Evolution of Diaphragm Thickness during Mechanical Ventilation. Impact of Inspiratory Effort. Am J Respir Crit Care Med 2015; 192(9):1080-8. doi: 10.1164/rccm.201503-0620OC
11. Grosu HB, Lee YI, Lee J, Eden E, Eikermann M, Rose KM. Diaphragm muscle thinning in patients who are mechanically ventilated. Chest 2012; 142(6):1455-1460. doi: 10.1378/chest.11-1638
12. Hadda V, Pahuja S, Mittal S, Madan K, Khan MA, Mohan A, Guleria R. Effects of Neurally Adjusted Ventilation Assist (NAVA) and conventional modes of mechanical ventilation on diaphragm functions: A randomized controlled trial. Heart Lung 2022; 53:36-41. doi: 10.1016/j.hrtlng.2022.01.016
13. Hickey SM, Sankari A, Giwa AO. Mechanical Ventilation. 2024 Mar 30. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024.
14. Hooijman PE, Beishuizen A, Witt CC, De-Waard MC, Girbes AR, Spoelstra-de-Man AM, Niessen HW, Manders E, Van-Hees HW, Van-den-Brom CE, Silderhuis V, Lawlor MW, Labeit S, Stienen GJ, Hartemink KJ, Paul MA, Heunks LM, Ottenheijm CA. Diaphragm muscle fiber weakness and ubiquitin-proteasome activation in critically ill patients. Am J Respir Crit Care Med 2015; 191(10):1126-38. doi: 10.1164/rccm.201412-2214OC
15. Hudson MB, Smuder AJ, Nelson WB, Bruells CS, Levine S, Powers SK. Both high level pressure support ventilation and controlled mechanical ventilation induce diaphragm dysfunction and atrophy. Crit Care Med 2012; 40(4):1254-60. doi: 10.1097/CCM.0b013e31823c8cc9
16. Jaber S, Petrof BJ, Jung B, Chanques G, Berthet JP, Rabuel C, Bouyabrine H, Courouble P, Koechlin-Ramonatxo C, Sebbane M, Similowski T, Scheuermann V, Mebazaa A, Capdevila X, Mornet D, Mercier J, Lacampagne A, Philips A, Matecki S. Rapidly progressive diaphragmatic weakness and injury during mechanical ventilation in humans. Am J Respir Crit Care Med 2011; 183(3):364-71. doi: 10.1164/rccm.201004-0670OC
17. Lawler JM, Powers SK. Oxidative stress, antioxidant status, and the contracting diaphragm. Can J Appl Physiol 1998; 23(1):23-55. doi: 10.1139/h98-002
18. Levine S, Nguyen T, Taylor N, Friscia ME, Budak MT, Rothenberg P, Zhu J, Sachdeva R, Sonnad S, Kaiser LR, Rubinstein NA, Powers SK, Shrager JB. Rapid disuse atrophy of diaphragm fibers in mechanically ventilated humans. N Engl J Med 2008; 358(13):1327-35. doi: 10.1056/NEJMoa070447
19. McConville JF, Kress JP. Weaning patients from the ventilator. N Engl J Med 2012; 367(23):2233-9. doi: 10.1056/NEJMra1203367
20. Pearson SD, Lin J, Stutz MR, Lecompte-Osorio P, Pohlman AS, Wolfe KS, Hall JB, Kress JP, Patel BK. Immediate Effect of Mechanical Ventilation Mode and Sedative Infusion on Measured Diaphragm Thickness. Ann Am Thorac Soc 2022; 19(9):1543-1550. doi: 10.1513/AnnalsATS.202111-1280OC
21. Petrof BJ, Jaber S, Matecki S. Ventilator-induced diaphragmatic dysfunction. Curr Opin Crit Care 2010; 16(1):19-25. doi: 10.1097/MCC.0b013e328334b166
22. Powers SK, Wiggs MP, Sollanek KJ, Smuder AJ. Ventilator-induced diaphragm dysfunction: cause and effect. Am J Physiol Regul Integr Comp Physiol 2013; 305(5):R464-77. doi: 10.1152/ajpregu.00231.2013
23. Rocco M, Maggi L, Ranieri G, Ferrari G, Gregoretti C, Conti G, DE Blasi RA. Propofol sedation reduces diaphragm activity in spontaneously breathing patients: ultrasound assessment. Minerva Anestesiol 2017; 83(3):266-273. doi: 10.23736/S0375-9393.17.11615-9
24. Schepens T, Verbrugghe W, Dams K, Corthouts B, Parizel PM, Jorens PG. The course of diaphragm atrophy in ventilated patients assessed with ultrasound: a longitudinal cohort study. Crit Care 2015; 19:422. doi: 10.1186/s13054-015-1141-0
25. Vassilakopoulos T, Zakynthinos S, Roussos CH. Respiratory muscles and weaning failure. Eur Respir J 1996; 9(11):2383-400. doi: 10.1183/09031936.96.09112383
26. Zambon M, Beccaria P, Matsuno J, Gemma M, Frati E, Colombo S, Cabrini L, Landoni G, Zangrillo A. Mechanical Ventilation and Diaphragmatic Atrophy in Critically Ill Patients: An Ultrasound Study. Crit Care Med 2016; 44(7):1347-52. doi: 10.1097/CCM.0000000000001657